

## Sodium Based Heat Pipe Modules for Space Reactor Concepts: Stainless Steel SAFE-100 Core

James J. Martin and Robert S. Reid

Marshall Space Flight Center, National Aeronautics and Space Administration, Huntsville, Alabama, 35812

Tel: (256) 544-6054, Fax: (256) 544-3396, jim.j.martin@nasa.gov

Tel: (256) 544-1523, Fax: (256) 544-3396, Robert.Reid@nasa.gov

**Abstract** – A heat pipe cooled reactor is one of several candidate reactor cores being considered for advanced space power and propulsion systems to support future space exploration applications. Long life heat pipe modules, with designs verified through a combination of theoretical analysis and experimental lifetime evaluations, would be necessary to establish the viability of any of these candidates, including the heat pipe reactor option. A hardware-based program was initiated to establish the infrastructure necessary to build heat pipe modules. This effort, initiated by Los Alamos National Laboratory and referred to as the Safe Affordable Fission Engine (SAFE) project, set out to fabricate and perform non-nuclear testing on a modular heat pipe reactor prototype that can provide 100-kWt from the core to an energy conversion system at 700°C. Prototypic heat pipe hardware was designed, fabricated, filled, closed-out and acceptance tested.

### I. INTRODUCTION AND APPROACH

Near-term ambitious space exploration would benefit from systems that have high specific power with associated high specific impulse. Nuclear electric propulsion systems have the potential to meet this requirement, offering a long life power rich environment in which to conduct scientific investigations<sup>1</sup>. A potential reactor concept for near term space exploration application of nuclear energy, to both in-space and surface power needs, is a compact fast spectrum heat pipe reactor system, a configuration that couples well to a number of power conversion systems including Brayton, Stirling, and thermoelectric. The benefits of the heat pipe reactor choice are its simple modular design that eases assembly, built in redundancy that minimizes single point failures, and a layout that is highly testable in a non-nuclear environment<sup>2,3,4</sup>. Non-nuclear evaluation allows for fast paced, cost effective development, identifying thermal hydraulic issues early on when changes can be easily implemented. This approach increases the probability of success should a costly full power ground nuclear demonstration be required<sup>5</sup>. Success of an early hardware test program will foster the continued development of infrastructure necessary to field larger, more capable systems in the future.

Alkali metal heat pipes have demonstrated reliability over multi-year operation and tolerance to many times the fast neutron fluence of expected core designs<sup>6</sup>. Alkali metal heat pipes have been successfully tested aboard the Space Shuttle Endeavor. Results correlated well with existing models, indicating that the first flight heat pipe core will operate as intended<sup>7</sup>. A large body of data documents the excellent compatibility of stainless steels with the vaporizing K and Na at temperatures up to 925°C<sup>8</sup>.

Since their invention 40 years ago, heat pipes using fluids such as ammonia and water have found wide use on earth and in space. The original heat pipe embodiment was intended expressly for space nuclear reactor energy conversion<sup>9</sup>. A heat pipe cooled reactor was the initial SP-100 baseline design<sup>10</sup>. Alkali metal heat pipes still occupy a niche associated mostly with space nuclear power systems. Despite the stunted US space reactor effort, R&D projects during the 1970s and 1980s sponsored by the DOE, NASA, and the US Air Force brought alkali metal heat pipes to a level of understanding and technical maturity unusual for space reactor components<sup>11</sup>. If heat pipe container and working fluid impurities can be kept low, care is taken in fabrication, and isolation is achieved from external contamination sources, long operating life is possible.

These conditions can be met with industry standard practice (ASTM C997-83, C1051-85, and G68-80)<sup>12,13,14</sup>.

As an initial step, the Marshall Space Flight Center Early Flight Fission – Test Facility (EFF-TF) team has taken the approach of establishing a hardware-based test program to evaluate potential reactor concepts; the heat pipe reactor system is one of those under evaluation<sup>15</sup>. Designed by Los Alamos National Laboratory and referred to as the Safe Affordable Fission Engine (SAFE), this concept has been implemented at multiple power levels. Work discussed in this paper relates to the 100-kW<sub>t</sub> design that is referred to as the SAFE-100. The SAFE-100 makes use of 61-stainless steel sodium heat pipe modules and has a nominal operating temperature of 973 K<sup>16,17</sup>. To lower project costs, a reduced version of the SAFE-100, core referred to as the SAFE-100a, has been fabricated. This configuration is identical to the SAFE-100 with the exception that only the central 19 heat pipe modules are used. For all tests, fission heating is simulated with specially designed electrical resistance heaters and electrical power control systems. Infrastructure has been established to fabricate, fill, process, and evaluate the heat pipe modules at a component level. These stainless steel heat pipes serve as an excellent forerunner to the fabrication and testing of higher temperature refractory metal heat pipe modules.

## II. OVERVIEW OF HEAT PIPE MODULE LIFETIME ISSUES

This section discusses some lifetime issues associated with alkali metal material systems. A striking advantage of the heat pipe core approach is the numerous temperature and power configurations offered. For instance, a single stainless steel heat pipe module can work with K or Na, allowing high power density compact reactor operating options from 800 K to 1173 K.

Lifetime issues are well established for alkali metal systems and are summarized in several textbooks<sup>18,19,20</sup>. When a heat pipe working fluid condenses, it is essentially free of impurities when compared with the adjacent wall. Nonmetallic impurities such as oxygen and carbon can diffuse from the condenser wall into the working fluid. These impurities may be carried toward the evaporator where they can concentrate. Impurities can precipitate and clog the wick, form low melting point eutectics with the container, or form ternary compounds with the container and working fluid.

If any of the elements in the wick or wall is soluble in the working fluid, they can dissolve and move to the evaporator end of the pipe. The heat pipe structure must be insoluble to avoid this condition. Proper material selection avoids this problem entirely. In the absence of non-metallic impurities, the solubility of stainless steel in K or Na is <<10 ppm (by weight).

Solubility of the wall in the working fluid increases in the presence of impurities when ternary compounds form with the working fluid and containment. Impurity corrosion rate in sodium heat pipes is related to the accumulation of elements such as O, N, and C in the heat pipe evaporator. Such impurity accumulation makes the corrosion rate somewhat dependent on mass fluence. The radial heat flux applied to the evaporator is  $\dot{q}_{rad} = \dot{q}/(\pi d L_e)$ , the mass flux through the evaporator is a function of the radial heat flux,  $G = \dot{q}_{rad}/h_{fg}$ , and the mass fluence through the evaporator is  $M'' = G\tau$ .

Mass diffusion transfers impurities from the heat pipe structure to the working fluid. The Arrhenius equation relates impurity diffusion rates to heat pipe temperature. As an initial approximation, data can be Arrhenius normalized for heat pipe tests conducted away from the operating temperature by:

$$\alpha(T) = \exp\left\{(\Delta H/k)\left[\frac{1}{T_0} - \frac{1}{T}\right]\right\}, \quad (1)$$

where  $k$  is Boltzmann's constant,  $T_0$  is the operating temperature,  $T$  is the heat pipe test temperature and  $\Delta H$  is the activation energy. Testing on the order of 100°C over the design temperature greatly accelerates the Arrhenius-governed diffusion rate in the heat pipe evaporator. Mass fluence can be accelerated by applying power along a shortened heat pipe evaporator length. Corrosion rates in stainless steel sodium material systems has been correlated with the expression<sup>21</sup>:

$$R = 1.103 \cdot 10^{-10} V^{0.884} O^{1.156} \cdot \exp\left[12.845 - \frac{13237}{T} - 0.00676 \frac{L}{D_i} + \frac{2.26}{\frac{t}{2.59 \cdot 10^6} + 1}\right] \quad (2)$$

## III. THE SAFE-100 MODULE DESIGN

The SAFE-100 is an intermediate stop along the path to a larger refractory metal system such as the SAFE-400 design<sup>22</sup>. This initial system requires 61 heat pipe modules fabricated from stainless steel with sodium as the working fluid. This system has been designed with the intention of coupling it to a heat exchanger capable of transporting thermal power to a Brayton power conversion system. For simplicity, each of the 61 SAFE-100 modules is identical in geometry and performance. The full power design was set at 100 kW<sub>t</sub>, requiring that each module operate at a nominal power throughput of 1.6 kW<sub>t</sub>. Based on previous experience with the SAFE-30 project<sup>23,24,25</sup>, a 30 kW<sub>t</sub> device, the new design makes use of symmetric evaporator

assembly, reducing stresses on the evaporator section that can result in module warping. The new layout, illustrated in Figure 1 has a tri-lobe arrangement with the fuel tubes set at  $120^\circ$  intervals about the evaporator perimeter. Analyses were performed to assess operating limits, setting the final module geometry.

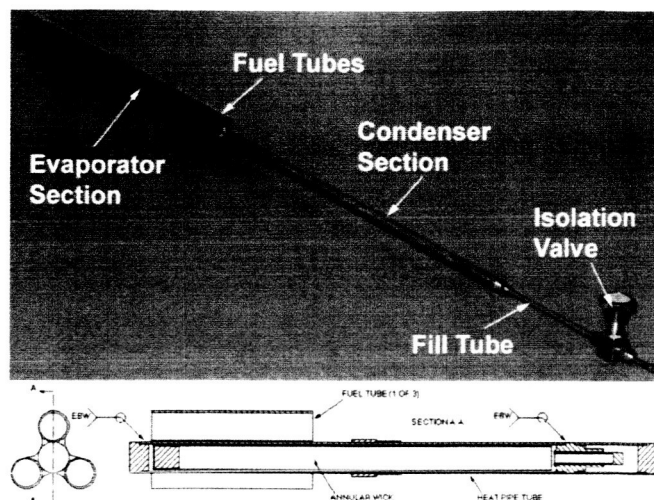


Figure 1. SAFE-100 heat pipe module layout.

The result is a module capable of satisfying the design heat transfer requirement (operating at approximately 20% of its design limit) at a nominal operating temperature of  $973^\circ\text{K}$ , as shown in Figure 2. The SAFE-100 heat pipe tube and three fuel tubes are constructed of stainless steel 321 with an outside diameter of 1.59 cm and wall thickness of 0.89 mm. The evaporator and condenser are of nearly equal lengths, with dimensions of 58.4 cm and 55.9 cm, respectively.

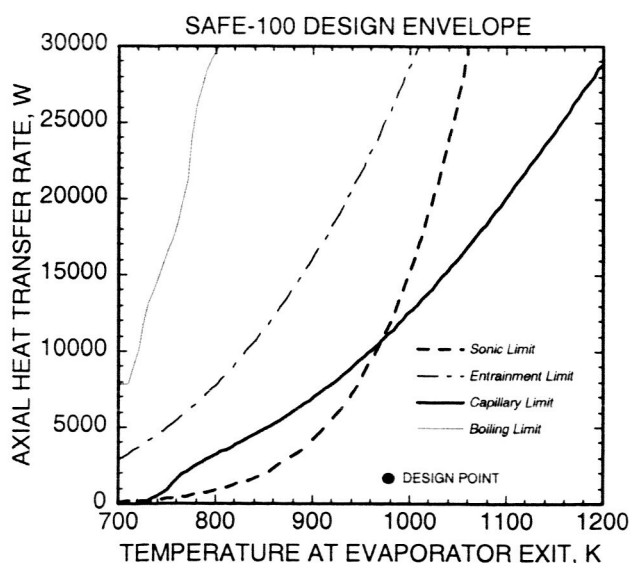


Figure 2. SAFE-100 sodium heat pipe design margins: axial heat transfer rate versus temperature at the evaporator exit.

The internal capillary channel is formed by a crescent annular wick composed of 7 layers of 400-mesh 304L stainless steel screen with a wire diameter 0.03 mm. Bubble point tests of the assembled wick structure (using ethyl alcohol and helium pressurant) measured a maximum wick pore diameter of  $16\ \mu\text{m}$ . The final geometry leaves a 0.6-mm annular-liquid flow gap between the module inner wall and outer edge of the wick<sup>26</sup>.

#### IV. FABRICATION OF THE SAFE-100 MODULE

The SAFE-100 modules are comprised of the following components: three fuel tube sections, central heat pipe tube, six tricusps, heat pipe end cap, heat pipe fill stem and internal wick/plug. Figure 3 illustrates the relative position of each of these components. The central heat pipe module (three fuel tubes, central heat pipe tube and six tricusps) is assembled by Hot Isostatic Pressing (HIP) which diffusion bonds the stainless steel components together at  $1100^\circ\text{C}$  and 1050 bar. The module outer end cap is electron beam welded in place and the sintered wick with tapered evaporator plug are placed inside. As a final assembly step during fabrication the fill stem is electron beam welded to the end of the condenser section. At each step of the process, strict cleanliness is maintained to avoid contamination. Several vacuum firings are performed on components during assembly at temperatures of  $900^\circ\text{C}$  with vacuum levels of  $10^{-5}$  Torr. A gaseous helium leak check is performed on the module before a final vacuum firing. The vacuum firing is followed by a back fill of dry pure argon before sealing and shipping the completed module to the MSFC<sup>27</sup>.

#### V. PROCESSING SAFE-100 MODULES

The capability to handle and dispense alkali metals has been established at the MSFC EFF-TF<sup>28</sup>. This procedure was applied to process SAFE-100 modules. Five steps are required to complete a heat pipe module: 1) filling the module with a known amount of sodium, 2) vacuum conditioning to remove any residual glove box argon, 3) leak checking, 4) closing out of the fill stem, and 5) high temperature wetting-in of the completed module. Fabricated modules are received in a condition ready for filling; they have been completely assembled, leak checked, vacuum fired at  $900^\circ\text{C}$ , then back filled with dry argon for transport from the fabrication contractor (Advanced Methods and Materials) to the MSFC laboratory. Module filling is performed in the fill machine, a glove box shown in Figure 4, using a known volume technique to meter a quantity of sodium ( $35 \pm 2$  grams). A fill is executed with a

two-stage process (Figure 5). First, the known volume is filled from the bulk sodium storage, followed by a transfer from the known volume to a heat pipe module. Weights are taken at both stages to verify sufficient material has been transferred.

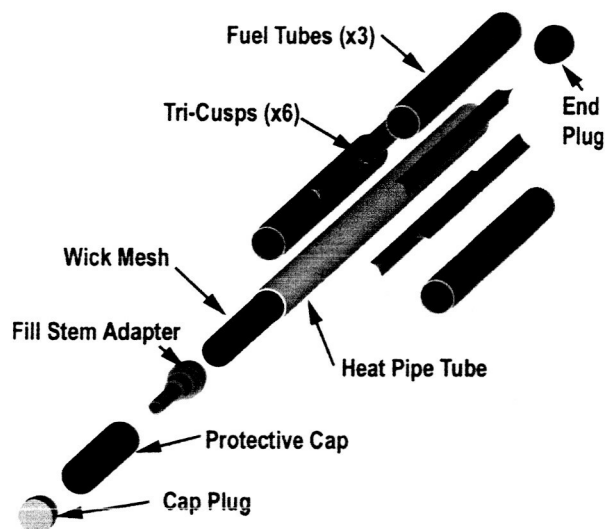


Figure 3. Exploded view of heat pipe module.

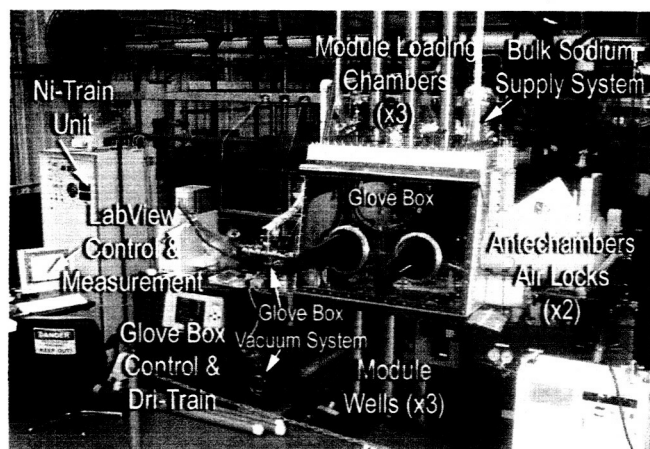


Figure 4. Alkali metal fill machine system.

The fill process is begun by connecting the known volume to the fill machine sodium system isolation valve/14-micron filter assembly (inside the glove box). The volume is then evacuated into the  $10^{-5}$  Torr range and all sodium feed lines are heated to the  $150^{\circ}\text{C}$  to  $160^{\circ}\text{C}$  range. The temperature is maintained at this level to minimize the solubility of oxygen in the sodium; the initial concentration in the bulk sodium stock is estimated at 10 parts per million (it was distillation purified from original DuPont Niapure stock at Los Alamos National Laboratory). All components are equipped with heaters and the known volume is maintained at approximately  $120^{\circ}\text{C}$  during the

transfer (sufficiently above the sodium melting point to minimize the chance of premature freezing).

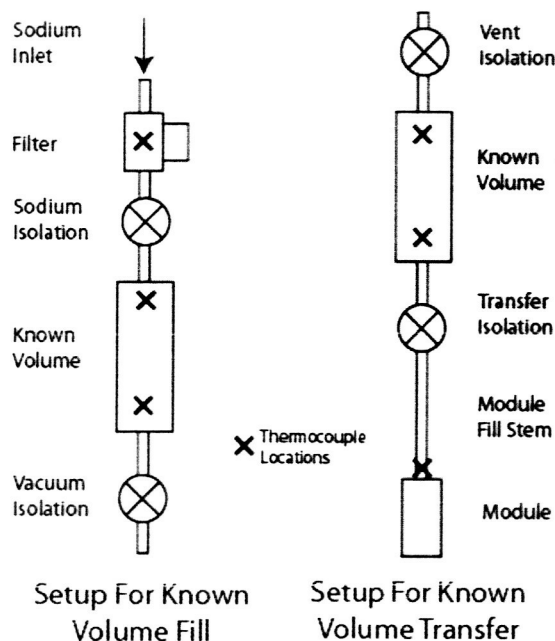


Figure 5. Fill/transfer hardware setups.

To initiate the transfer, a pressure of 760 Torr (high purity Argon) is placed on the sodium feed system and the isolation valve is opened. Temperatures on the module are monitored; a rapid jump in the known volume temperature indicates a successful fill (Figure 6). The heaters are turned off and the volume allowed to cool. During cool down, the temperature plateau during sodium phase transition is a second indicator that the transfer was successful. The known volume is removed and weighed to determine the quantity of sodium transferred. The volume is then placed on an evacuated ( $10^{-5}$  Torr range) heat pipe module in preparation for transfer. The vacuum provides the pressure differential required to transfer the molten sodium. The volume and module fill stem are fitted with heaters and temperatures are increased to approximately  $170^{\circ}\text{C}$  on the known volume and  $120^{\circ}\text{C}$  on the heat pipe module fill stem. The isolation valve is then opened and sodium flows into the heat pipe module; during the transfer, the temperature on the module fill stem jumps rapidly while the molten sodium flows past, as shown in Figure 7. The temperature of the known volume typically climbs higher during the heater "on" cycle after transfer since its thermal mass has been significantly reduced. An additional indication that the transfer was successful is the lack of a sodium phase transition temperature plateau during the module/known volume cool down.

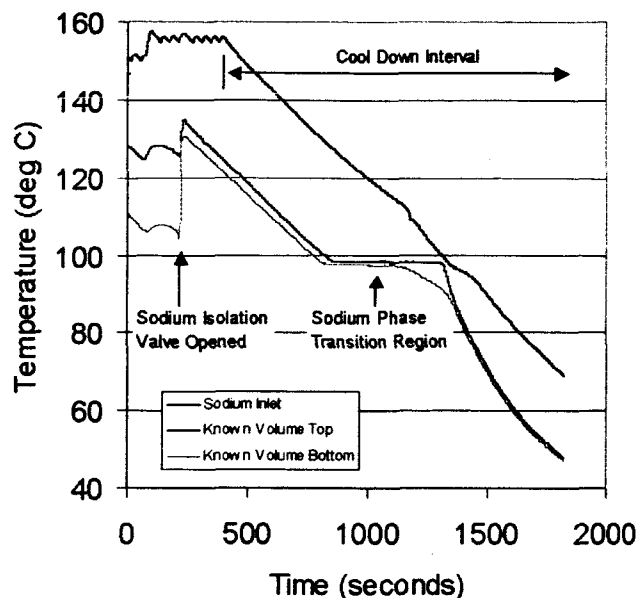


Figure 6. Sodium transfer from fill machine to known volume: temperature versus time traces.

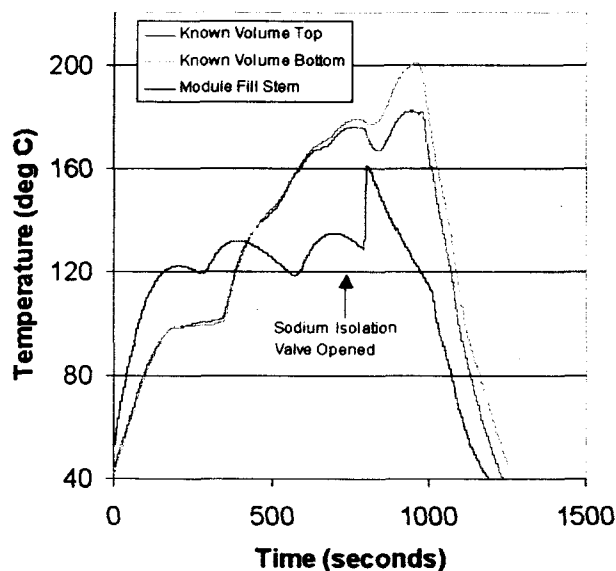


Figure 7. Sodium transfer from known volume to heat pipe module: temperature versus time traces.

The filled module is evacuated to the mid  $10^{-7}$  Torr range and leak checked using a Varian Model 979 leak detector that detects a baseline leak rate of  $0.2 \times 10^{-11}$  standard cc/sec of helium. Helium is then sprayed around the fill stem connection fittings and module welds; any increase above the background rate is readily picked up and displayed. Fittings are tightened as required to make the unit leak tight. At this point, the module is approved for removal from the glove box for further processing. The next step requires hooking the module up to an ultra high

( $10^{-8}$  to  $10^{-9}$  Torr range) vacuum turbo pump system so that it can be heat processed to remove trapped gas. Heaters are placed along the full module length and thermocouples are located on the evaporator and condenser sections. The module is evacuated into the low  $10^{-8}$  Torr range, leak checked again, and then heated to the  $200^{\circ}\text{C}$  to  $250^{\circ}\text{C}$  range. This heating cycle continues for approximately 1 hour or until the pressure falls back into the  $10^{-8}$  Torr range. Heating allows the sodium to flow freely and to release any argon trapped during the module fill process. The general trend is an initial pressure rise (during heat up) followed by a series of very short-term pressure spikes and then a slow steady drop. Tapping the module as the pressure drops produces small pressure spikes that decrease in amplitude and duration while the heating cycle continues. This behavior is observed in Figure 8.

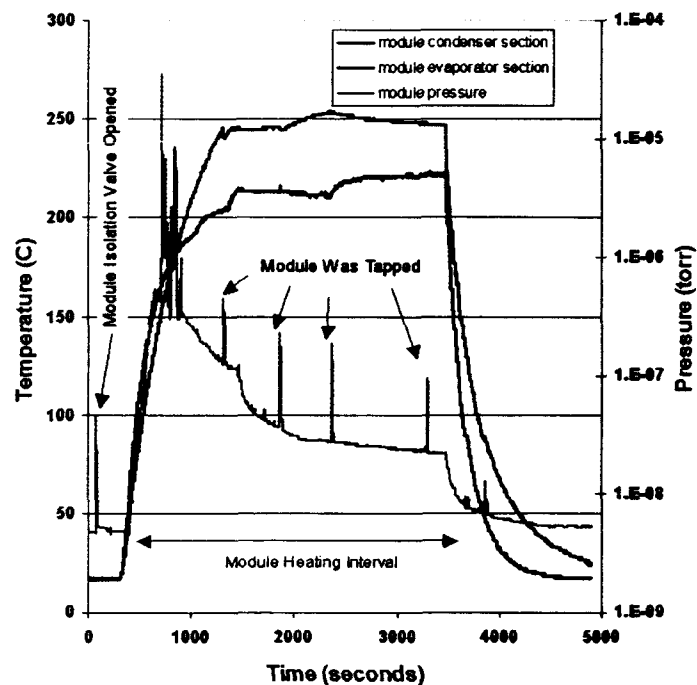


Figure 8. Vacuum conditioning of a filled sodium heat pipe module.

The module is cooled, isolated from the vacuum system, and its fill stem is pressed using 2.5-cm wide steel dies at a load of approximately 20 metric tons. The module is then placed back into the glove box and the flat-pressed fill stem area is cut off/welded using a tungsten inert gas (TIG) welder. Performing a fusion cutoff with the TIG welder maintains an excellent molten stainless steel seal across the stem, preventing glove box argon from getting into the heat pipe module. The welded stem is visually inspected and then sealed off with a 7.5-cm long cap that contains the dry glove box argon, providing both protection and a secondary seal (Figure 9). The capped module is then

placed in a vacuum furnace operating in the low  $10^{-5}$  Torr range for a 48-hour "wet-in" cycle at approximately  $750^{\circ}\text{C}$ . This "wet-in" process allows the sodium to fully wet the interior of the module (walls and capillary mesh structure). The temperature is ramped up over a two-hour period, held constant for the 48-hour duration, and then cooled using an ambient furnace cooling cycle. The "wet-in" cycle improves both startup characteristics and performance at high heat flux and minimizes the potential for evaporator or condenser dry out.

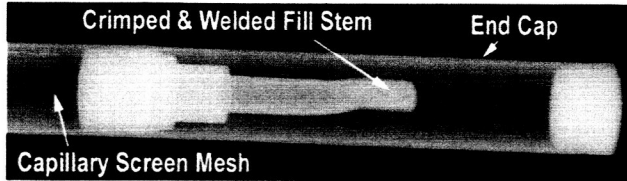


Figure 9. X-Ray of heat pipe.

## VI. ACCEPTANCE TESTING THE SAFE-100 MODULE

The finished modules undergo final acceptance testing prior to integration into the SAFE-100a system. This involves operating the module at a steady state condenser temperature in the  $650^{\circ}\text{C}$  to  $750^{\circ}\text{C}$  range (covering nominal SAFE-100a operation). To accomplish this, the module is equipped with three electric heater elements (measuring approximately  $2/3^{\text{rd}}$  the length of the evaporator section) and fifteen type-K thermocouples that are spot welded to the module surface (Figure 10).

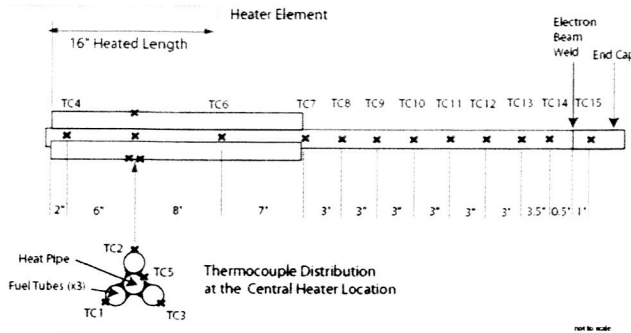


Figure 10. Module instrumentation layout.

Three thermocouples are located on the heater tubes, three on the evaporator section and nine on the condenser. The modules are operated in air with an approximate 1-hour startup leading into the 6-hour steady state hold at temperature. To limit the module's evaporator heat loss, the evaporator section is wrapped in an insulation blanket with a thickness of approximately 10 cm. The condenser is exposed to allow natural convection to remove the input power (Figure 11).



Figure 11. Sodium stainless steel heat pipe module operating in air near  $700^{\circ}\text{C}$ .

Figure 12 illustrates the typical startup transient for a particular module at a condenser temperature of  $670^{\circ}\text{C}$ . The condenser section thermocouple traces show thaw occurring when the evaporator reaches a temperature of approximately  $500^{\circ}\text{C}$  (corresponding to a vapor pressure of 9 Torr). The sodium vapor pressure at the final steady-state temperature is 185 Torr; to reach one atmosphere pressure (760 Torr) an evaporator temperature of  $790^{\circ}\text{C}$  is required. The module condenser temperature varies by approximately  $20^{\circ}\text{C}$  from the evaporator exit to the end of the condenser (Figure 13). This temperature difference is reduced as evaporator temperature (vapor pressure) is increased.

A power balance can be assessed for the heat pipe to provide an estimate of the power that is lost to the environment along the condenser section. This is approximated as the difference in the input power (evaporator heater power) and that lost through the evaporator insulation blanket,

$$Q_{cond} = Q_{evap} - Q_{loss} \quad (3)$$

The loss term can be assessed by solid conduction in the blanket material,

$$Q_{loss} = \frac{k_{avg} A_{ins} (T_{inner} - T_{outer})}{l_{thickness}} \quad (4)$$

For the module test conditions the resulting condenser power  $Q_{cond}$  was found to be 1.25 kW (1.58 kW input power  $Q_{evap} - 0.33 \text{ kW } Q_{loss}$ ). This assessment can be verified by inspecting the heat transfer of the condenser section to the environment, that includes heat transfer by both radiation and convection<sup>29</sup>. This can be written as:

$$Q_{cond} = Q_{rad} + Q_{conv}, \quad (5)$$

$$Q_{rad} = \sigma \epsilon \pi d L_c (T_c^4 - T_a^4), \quad (6)$$

$$Q_{conv} = 1.42 \pi d L_c^{3/4} (T_c - T_a)^{5/4}. \quad (7)$$



For the module conditions being evaluated, the power dissipated from the condenser section  $Q_{cond}$  was found to be 1.24 kW, which compares well to the evaporator assessment of 1.25 kW. The completed heat pipe units that pass acceptance testing are incorporated into the SAFE-100a hardware setup. This configuration is a full-up system evaluation in which all modules shall be operated together with an integrated heat exchanger to actively remove heat from the condenser section.

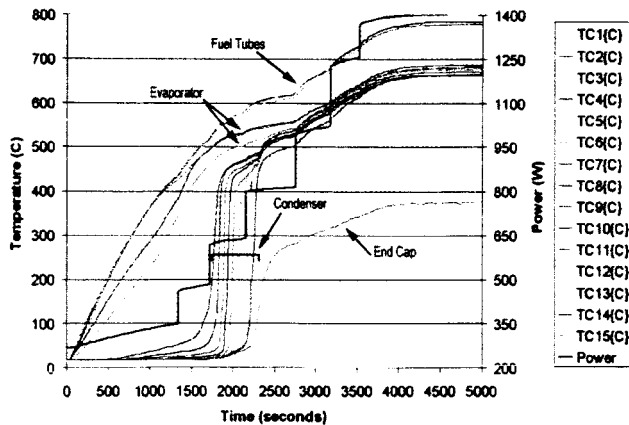


Figure 12. Sodium heat pipe module startup: temperature profile versus time.

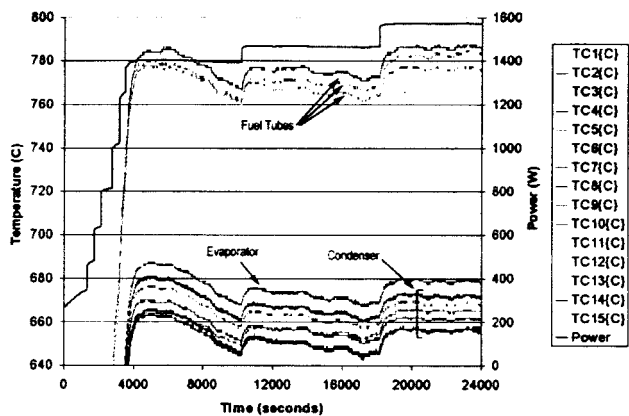


Figure 13. Sodium heat pipe module temperature profile during steady state operation.

## VII. SUMMARY

To begin the verification process, a hardware program was initiated to investigate fabrication and operation of a number of sodium-filled stainless steel heat pipes with geometry prototypic of a heat pipe reactor system. Thirty-five modules have been constructed; 19 modules have been filled and acceptance tested. Each completed module was filled with  $35 \pm 2$  grams of sodium, closed out, and then successfully operated in excess of  $650^\circ\text{C}$  for over 6 hours. All 19 filled modules passed the acceptance test. The 19 completed modules will be integrated into the SAFE-100a

configuration. Throughout all heat pipe-processing operations, close attention was paid to the number of steps that were taken and a detailed set of procedures was developed to document the process. This information serves as a working guide should a full complement of modules be required.

## ACKNOWLEDGMENTS

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## NOMENCLATURE

$A_{ins}$	= insulation surface area ( $\text{m}^2$ )
$d$	= condenser diameter (m)
$G$	= mass flux ( $\text{kg}/\text{m}^2\text{-s}$ )
$h_{fg}$	= latent heat of vaporization ( $\text{J}/\text{kg}$ )
$k_{avg}$	= insulation thermal conductivity ( $\text{W}/\text{m-K}$ )
$l_{thickness}$	= insulation thickness (m)
$L_c$	= condenser length (m)
$L_e$	= evaporator length (m)
$M''$	= mass fluence ( $\text{kg}/\text{m}^2$ )
$Q_{conv}$	= convective loss (W)
$Q_{cond}$	= condenser power (W)
$Q_{evap}$	= evaporator power (W)
$Q_{loss}$	= parasitic losses from evaporator (W)
$Q_{rad}$	= radiation loss (W)
$\dot{q}_{rad}, \dot{q}$	= radial heat flux ( $\text{W}/\text{m}^2$ )
$T_a$	= ambient temperature (K)
$T_c$	= condenser temperature (K)
$T_{inner}$	= Insulation inner temperature (K)
$T_{outer}$	= Insulation outer temperature (K)
$\sigma$	= Stefan-Boltzmann constant ( $\text{W}/\text{m}^2\text{-K}^4$ )
$\epsilon$	= total hemispherical emittance (-)
$\tau$	= time (s)

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